(12) UK Patent Application (19) GB (11) 2 301 902 (13) A

(43) Date of A Publication 18.12.1996

(21) Application No 9611667.8

(22) Date of Filing 05.06.1996

(30) Priority Data
(31) 08488626 (32) 08.06.1995 (33) US

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(51) INT CL[6]
G01V 3/30

(52) UK CL (Edition O)
G1N NCLE N19B2A N19B2Q N19D1X

(56) Documents Cited
GB 2256715 A GB 2194345 A WO 92/22833 A1
US 5241273 A US 5230386 A US 5045795 A

(58) Field of Search
UK CL (Edition O) G1N NCLA NCLC NCLE NCLF NCLH
INT CL[6] G01V
Online: WPI

(54) Detecting boundaries between strata while drilling a borehole

(57) A quantative geosteering method utilizes a measurement while drilling dual frequency resistivity tool to measure the electromagnetic properties of a formation at the same time and location at two different frequencies resulting in four depths of investigation, whereby sufficient information is yielded for solving the problem of an approaching bed in a geosteering mode. That is, it is possible to determine the distance of the tool from an approaching bed and it is also possible to estimate the resistivity of the approaching bed. In geosteering, the primary depth of interest is the depth to the contact with another formation. There are three unknowns in the problem (i.e., the distance to the upcoming bed, the resistivity of the pay zone, and the resistivity of the upcoming formation). This problem is solved, on a computer, generally uphole at the surface, utilizing a simple nonlinear regression scheme e.g, a high angle dipping model inversion using at least three independent data points i.e., at least three of the four depths of investigation, to resolve the three unknowns identified above, and thereby determine the distance.

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FIG. 1A

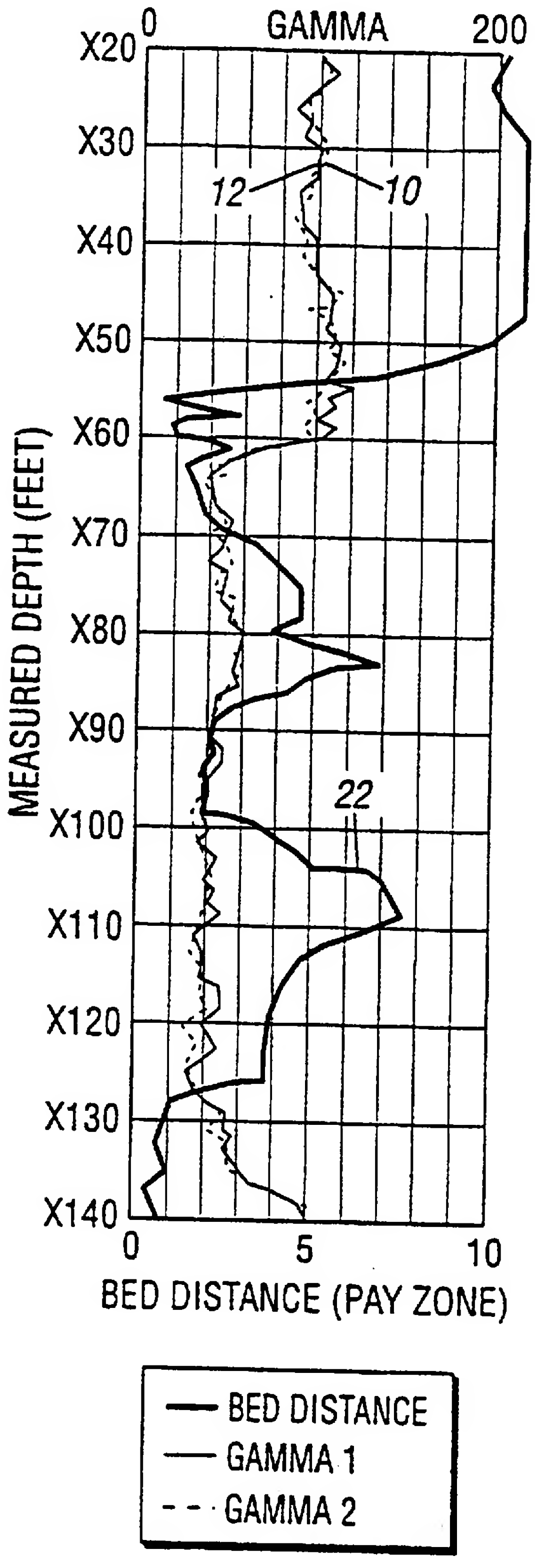
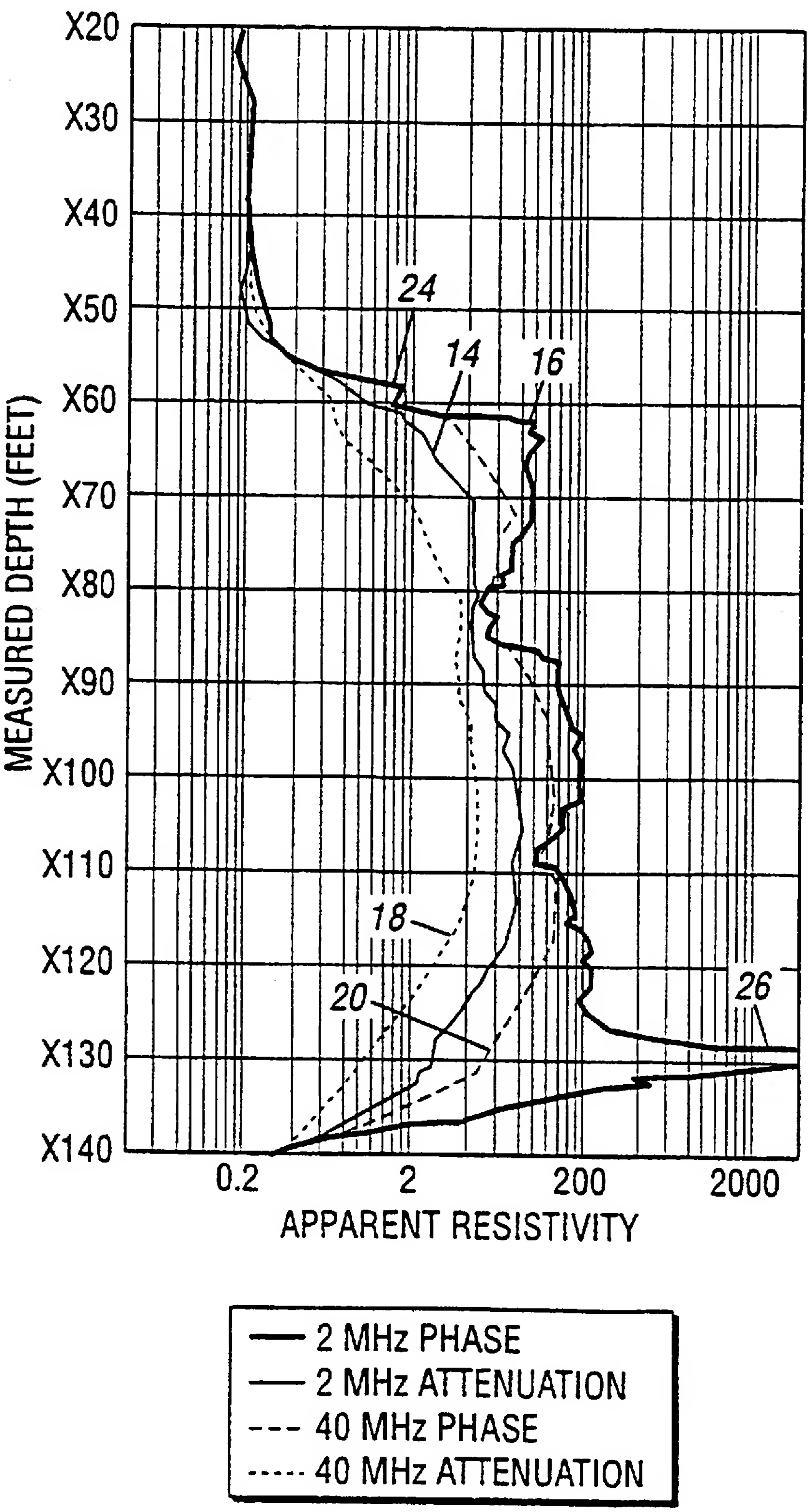

0
GAMMA
200
X20
X30
X40
X50
X60
X70
X80
X90
X100
X110
X120
X130
X140
12
10
22
MEASURED DEPTH (FEET)
0
5
10
BED DISTANCE (PAY ZONE)
BED DISTANCE
GAMMA 1
GAMMA 2

FIG. 1B



X20
X30
X40
X50
X60
X70
X80
X90
X100
X110
X120
X130
X140
MEASURED DEPTH (FEET)
0.2
2
200
2000
APPARENT RESISTIVITY
24
14
16
18
20
26
2 MHz PHASE
2 MHz ATTENUATION
40 MHz PHASE
40 MHz ATTENUATION

FIG. 2A

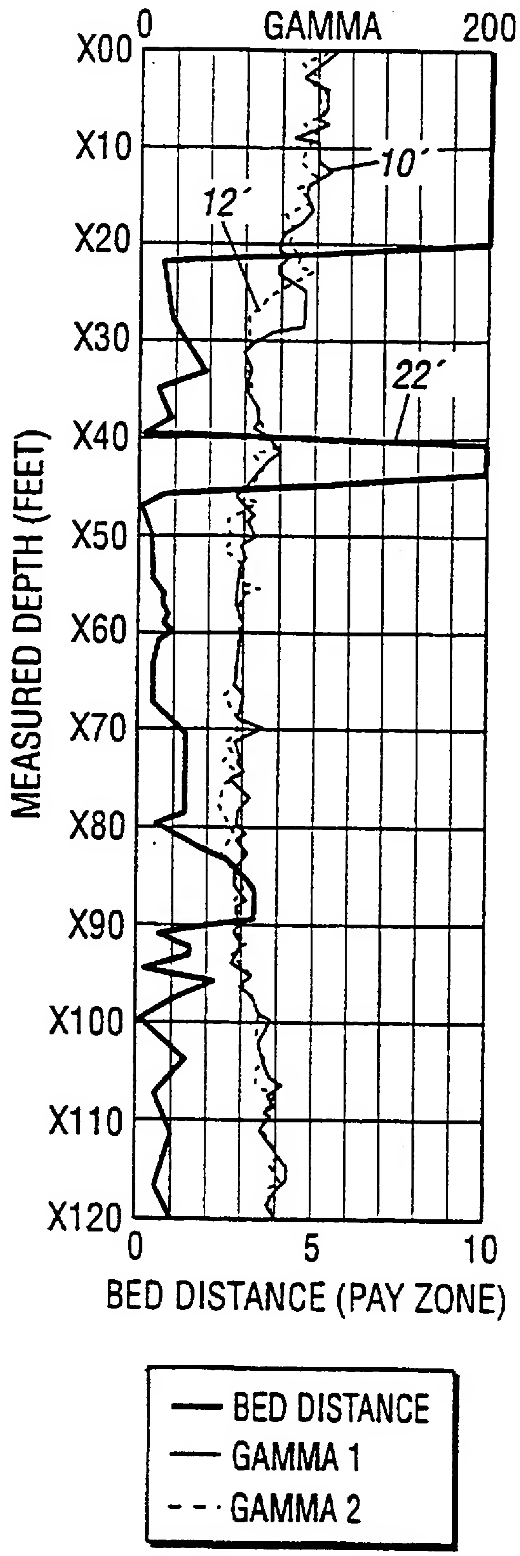
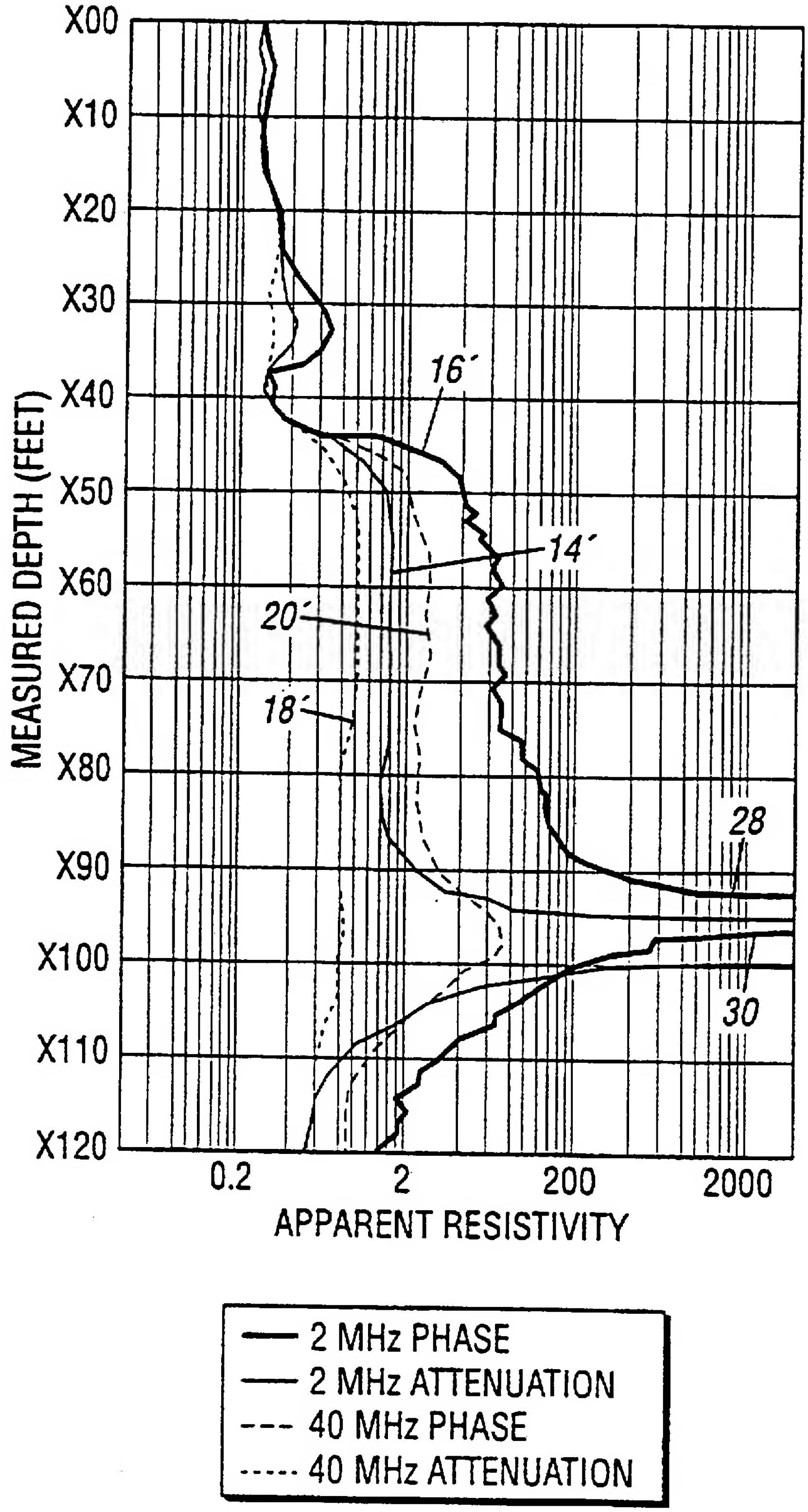

GAMMA
0
200
X00
X10
X20
X30
X40
X50
X60
X70
X80
X90
X100
X110
X120
MEASURED DEPTH (FEET)
10'
12'
22'
0
5
10
BED DISTANCE (PAY ZONE)
BED DISTANCE
GAMMA 1
GAMMA 2

FIG. 2B


MEASURED DEPTH (FEET)
X00
X10
X20
X30
X40
X50
X60
X70
X80
X90
X100
X110
X120
16'
14'
20'
18'
28
30
0.2
2
200
2000
APPARENT RESISTIVITY
2 MHz PHASE
2 MHz ATTENUATION
40 MHz PHASE
40 MHz ATTENUATION

DRILLING A WELLBORE

The present invention relates generally to drilling a wellbore using a measurement-while-drilling facility. It can be used for quantitative geosteering utilizing a nonlinear regression scheme for determining the distance to the nearest bed.

Directional drilling involves the drilling of a wellbore along a deviated course in order to bottom out in a target region at a particular vertical and horizontal distance from the original surface location. Directional drilling is employed, for example, to obtain an appropriate well bore trajectory into an oil producing formation bed (or "pay zone') and then drill substantially within the pay zone. A horizontally drilled well can greatly increase the borehole volume in the pay zone with attendant increase in oil production. Recent advances in directional drilling equipment and techniques some of which are referenced hereinbelow, have greatly improved the efficiency of certain drilling operations.

Before a directional drilling well plan is devised, the drilling team will usually have significant a prior knowledge of geological attributes of the local formations. This knowledge may be derived, for example, from survey and/or producing wells in the local area. Accordingly, in the directional drilling process, expected formation bed boundaries may be sought as markers from which to implement trajectory changes in the well bore. These boundaries are typically determined using borehole logging equipment; e.g. with so-called "wireline" logging equipment, wherein measurements are taken in a well bore (with the drill string removed) by lowering one or more logging devices in the well bore on a cable and taking measurements with the device(s) as the cable is withdrawn, and/or with so called "logging-while-drilling" equipment wherein one or more logging devices are mounted on the drill string near the bit. Logging-while-drilling has obvious

advantages for directional drilling in that trajectory changes, made in response to logging information, can be implemented without pulling the drill string.

Resistivity logging, which measures the electrical resistivity of formations surrounding an earth borehole, is a commonly used technique of formation evaluation. In so-called propagation resistivity logging, which is well suited to logging-while-drilling, energy is transmitted into the formations and propagates therein. Energy shed back into the borehole is measured at a receiver to obtain a phase measurement and an amplitude measurement, or an in-phase measurement and an out-of-phase measurement. Two closely-spaced receivers are traditionally used and the phase difference between the two receivers and their amplitude ratio (i.e., attenuation) are usually calculated. In some tools, the phase difference and amplitude ratio are directly measured across a pair of receivers.

A signal received in a first, so-called "far", receiving antenna is shifted in phase and its amplitude will be less than the signal received in a second, so-called "near", receiving antenna. Resistivities can then be derived from both the phase difference (R_{pd}) and the amplitude ratio (R_{ad}) of the received signals. The differential measurement is primarily responsive to the formation opposite the receiving antennas and is less sensitive to the borehole and/or variations in the transmitted signal as in prior art sensing devices. An example of a formation evaluation instrument of this type is described in FIGURES 1 and 2 of U.S. Patent No. 5,001,675 which is assigned to the assignee hereof and fully incorporated herein by reference. The formation evaluation tool acquires the resistivity data in real time and then transmits this information to the drilling operator using any suitable measurement-while-drilling transmission technique such as mud pulse telemetry or the information is stored downhole for review after retrieval of the tool.

The resistivity logging values obtained from the described type of propagation logging device are useful in determining formation resistivity at two depths of investigation, and can also be used to locate bed boundaries under most conditions, such

as by observing crossovers between R_{ps} and R_{ad}. However, when there is substantial invasion of the formations by the drilling fluid, bed boundary delineation can suffer. Also, there are situations which arise in directional drilling, particularly horizontal drilling, when improved bed boundary delineation may be desirable or necessary. Consider, for example, the situation where horizontal drilling has been initiated in a pay zone and it is desired to maintain a course in the pay zone and adjacent a boundary to the pay zone. As the drill path approaches the boundary at a very small angle (e.g., almost parallel to the boundary, which is a dip angle close to 90 degrees) it would be advantageous to know the boundary has been approached or reached as soon as possible (in terms of either time or position), and to be able to identify the location of the boundary with good accuracy. In such circumstance, prior boundary determination techniques may be inadequate, and the directional drilling operation can lose efficiency as steering corrections are missed or made at the wrong position, in the wrong direction, or later than they should be.

It is known that under certain conditions the resistivity measurements obtained with logging equipment, such as induction logging devices, exhibit horns at formation geological bed boundaries. (see, for example, T. D. Barber & A.Q. Howard, "Correcting the Induction Log for Dip Effect", SPE 64th Annual Technical Conference, San Antonio (Oct. 1989), Paper SPE 19607; A. Q. Howard & W. C. Chew, "A Variational Model of Induction Logging in a Dipping Bed Environment", IGARSS Symposium, Vancouver (Jul. 10 - 14, 1989), Session F8, Paper 5.) The horns, which occur in electromagnetic logging tools as well as induction tools, are caused by polarizations at the boundaries. In the prior art, such as in induction logging, horns are considered an unfortunate anomaly, and substantial effort has been expended to eliminate horns, for example by applying appropriate post-processing.

U.S. Patent No. 5,230,386 to Wu et al and U.S. Patent No. 5,241,273 to Luling teach utilization of the horns, in the resistivity response of an electromagnetic

propagation resistivity logging device, in the steering of directional drilling apparatus with respect to a formation bed boundary. However, the horns occur very close the bed boundary so any correction made using these horns will generally occur after the drill bit has entered he neighbouring formation.

The above-discussed and other drawbacks and deficiencies of the prior art are overcome or alleviated by the present invention which is set out in claim 1. In accordance with the preferred embodiment of the present invention, a measurement while drilling dual frequency resistivity tool measures the electromagnetic properties of a formation at the same time and location at two different frequencies resulting in four depths of investigation, whereby sufficient information is yielded for solving the problem of an approaching bed in a geosteering mode. That is, it is possible to determine the distance of the tool(and thereby the drill bit) from an approaching bed and it is also possible to estimate the resistivity of the approaching bed.

In geosteering, the primary depth of interest is the depth to the contact with another formation. Generally, the tool is in a pay zone and the most important purpose of the resistivity measurement is to detect the so-called "cap rock" or the so-called "wet zone" before the bit drills into it. There are three unknowns in the problem (i.e., the distance to the upcoming bed, the resistivity of the pay zone, and the resistivity of the upcoming formation). This problem is solved, on a computer, generally uphole at the surface, utilizing a simple nonlinear regression scheme e.g. a high angle dipping model inversion using at least three independent data points e.g. at least three of the above described 2MHz and 400 KHz, attenuation and phase difference measurements, to resolve the three unknowns identified above, and thereby determine the distance .

While a dual frequency resistivity device is described above, it will be appreciated that any device that produced three independent depths of investigation can

be used to calculate the three unknowns. For example, phase difference and amplitude ratio at two different longitudinal transmitter-receiver spacings on the drillstring provide four depths of investigation. Phase difference (or attenuation) alone at three or more longitudinal transmitter-receiver spacings on the drillstring could also be used.

A method for identifying bed boundaries by using formation modeling is described in U.S. Patent No. 5,230,386, but the present invention carries the process much further by calculating the distance from the bed boundary using the propagation resistivity data, thereby assuring that the drilling operator has the ability to make corrections in the drilling process prior to the drill bit entering a neighboring formation.

The above-discussed and other features and advantages of the present invention will be appreciated and understood by those skilled in the art from the following detailed description and drawings.

Referring now to the drawings wherein like elements are numbered alike in the several FIGURES:

FIGURE 1A is a plot of gamma ray and calculated distance to the nearest bed curves against measured depth in a nearly horizontal well;

FIGURE 1B is a plot of apparent resistivity curves calculated from 2 MHz attenuation and phase difference, and 400 kHz attenuation and phase difference curves against measured depth in the well of FIGURE 1A;

FIGURE 2A is a plot of gamma ray and calculated distance to the nearest bed curves against measured depth in another nearly horizontal well; and

FIGURE 2B is a plot of apparent resistivity curves calculated from 2 MHz attenuation and phase difference, and 400 kHz attenuation and phase difference curves against measured depth in the well of FIGURE 2A.

Propagation resistivity tools for measurement while drilling utilizing two frequencies from the same transmitter-receiver array have recently become commercially available. A 400 kHz measurement along with the traditional 2 MHz propagation resistivity measurement results in doubling the number of depths of investigation and increasing the depth of investigation. The addition of a second frequency (e.g., 400 kHz) results in four depths of investigation (i.e., an attenuation and a phase at each frequency) instead of two depths for a traditional 2 MHz only tool. In a mud-motor-integrated device specifically designed for geosteering, the increase in depth of detection is particularly important in horizontal drilling. In accordance with the present invention, the four depths of investigation allow for the calculation of the distance from an approaching bed in horizontal drilling.

By way of example, a two-frequency propagation resistivity tool useful for geosteering is commercially available as the NaviGator™ from Baker Hughes Incorporated, the assignee hereof, see generally, Meyer, W.H., Wu, J.Q., Macune, D.T., and Harvey, P.R., 1994, Near-Bit Propagation Resistivity for Reservoir Navigation, presented at the SPE 69th Annual Technical Conference, September 25-28, paper SPE 28318, which is incorporated herein by reference. This tool has a single transmitter-receiver separation of about thirty-five inches, but it transmits at two frequencies (i.e., 2 MHz and 400 kHz). The result is four depths of investigation, i.e., both attenuation and phase difference resistivity at two frequencies. The received signals are transmitted uphole using measurement while drilling telemetry (e.g., mud pulse or acoustic telemetry), as is well known.

The tool measures the electromagnetic properties of the formation at the same time and location at two different frequencies which doubles the number of depths of investigation. In accordance with the present invention, sufficient information is yielded for solving the problem of an approaching bed in a geosteering mode. That is, it is

possible to determine the distance of the tool from an approaching bed and it is also possible to estimate the resistivity of the approaching bed.

When drilling horizontally the radial direction relative to the tool is up, down, or deeper into the formation rather than merely deeper into the formation as it is in the vertical-hole mode. This change in geometry causes a change in the definition of depth of investigation. In geosteering, the primary depth of interest is the depth to the contact with another formation. Generally, the tool is in a pay zone and the most important purpose of the resistivity measurement is to detect the so-called "cap rock" or the so-called "wet zone" before the bit drills into it. With three or more depths of investigation the distance to the upcoming bed boundary can be determined. There are three unknowns in the problem (i.e., the distance to the upcoming bed, the resistivity of the pay zone, and the resistivity of the upcoming formation). This problem is solved, on a computer generally uphole at the surface, utilizing a simple nonlinear regression scheme e.g., a high angle dipping model inversion using at least three independent data points i.e., at least three of the above described 2 MHz and 400 kHz, attenuation and phase difference measurements, to resolve the three unknowns identified above. By way of example, such a nonlinear regression is taught in an article entitled Resistivity Inversion With Ridge Regression, by Inman, Geophysics, Vol. 40 #5, pp. 798 - 817, 1975, which is expressly incorporated herein by reference.

While a dual frequency resistivity device is described above, it will be appreciated that any device that produced three independent depths of investigation can be used to calculate the three unknowns. For example, phase difference and amplitude ratio at two different longitudinal transmitter-receiver spacings on the drillstring provide four depths of investigation. Phase difference (or attenuation) alone at three or more longitudinal transmitter-receiver spacings on the drillstring could also be used.

Referring to FIGURES 1A-B, data obtained from drilling operations in the Gulf of Mexico from measurement while drilling tools on a drillstring near the drill bit are

plotted against measured depth (i.e., the overall length of drillstring) in a nearly horizontal well. Two gamma ray curves 10 and 12 indicate that this well is being drilled down through a shale into a sandstone. The driller maintained the true vertical depth but the tool seems to leave the pay zone and return to the shale near X135 feet. Four apparent resistivity curves 14, 16, 18 and 20 never come completely together in any part of the pay zone, indicating that the deeper measurements are still being affected by the nearby shale.

The shallowest measurement is the 2 MHz phase difference (curve 16); it reads the highest resistivity of any of the measurements because it is least able to detect the neighboring shale. In fact, the 2 MHz phase difference curve 16 reads very close to the true resistivity of the pay zone, this information is provided by the regression which must calculate the true formation resistivity and the shale resistivity along with the distance to the shale. The 400 kHz attenuation (curve 18) is the deepest measurement (see Meyer, W.H., Wu, J.Q., Macune, D.T., and Harvey, P.R., 1994, Near-Bit Propagation Resistivity for Reservoir Navigation, presented at the SPE 69th Annual Technical Conference, September 25-28, paper SPE 28318, which is incorporated herein by reference); the 2 MHz phase difference (curve 16) is the shallowest measurement, and the other two measurements (curves 14 and 20) fall in between, the 2 MHz attenuation (curve 14) is usually deeper than the 400 kHz phase difference (curve 20). The measurement with the lowest resistivity is the deepest because it is measuring more of the nearby conductive shale. Therefore, the order of depths of investigation in FIGURE 1B is: 2 MHz phase difference (shallowest), 400 kHz phase difference, 2 MHz attenuation, and 400 kHz attenuation (deepest).

In accordance with the present invention, the calculated distance to the nearest bed is plotted as a curve 22 along with the two gamma rays curves 10 and 12. At depths below X45 the regression doesn't reach the minimum criteria for detection of a bed; therefore a large number for bed distance is plotted. This is the normal case when the

tool is in a bed that is more conductive than the approaching bed. The propagation resistivity tools sense conductivity so their ability to detect resistive zones is limited. However, once the tool is in the resistive zone it can easily detect nearby conductive beds.

In FIGURES 1A-B there is a small horn 24 in curve 16 (i.e., 2MHz phase difference) as the tool enters the pay zone at X60 feet. This horn 24 confuses the regression to some extent both here and at X130 where a larger horn 26 appears when the bed is exited. When the 2 MHz phase difference resistivity begins to show a horn (24 or 26), the regression scheme has some difficulty and the measurements are not very reliable. Specifically, the calculated value of true resistivity (Rt) in the pay zone is no longer accurate since the shallow measurements (i.e., phase differences) are perturbed by the horns. The presence of the horns also causes inaccuracy in the measurement of distance to the approaching bed. However, by the time the exiting horn 26 is seen, the presence of the boundary has been observed for some time and corrective action should have been taken if it was desired, such action was not taken in this example. That is, the operator of the well was aware of the approaching bed boundary, but choose not to make a steering adjustment because staying in this pay zone was not his highest priority. Nevertheless, this illustrates the principle features of this invention.

In two places (i.e., X80 and X105 feet) a maximum of about seven feet bed distance is plotted. However, the phase differences, which are the shallowest measurements, are the measurements which appear to react to bring the curves together at these two points. When the curves come together the situation appears to be more homogeneous, so a larger depth to the bed is computed by the program. However, in the case of these two zones, this interpretation is suspect because the shallow curves have moved toward the deeper curves when the opposite would be expected if the bed distance were increasing. These calculations are made on the data at each depth rather than using

the entire data set, as would be done in deconvolution. Therefore, this technique can be used in real time for geosteering.

Referring to FIGURES 2A - B, another Gulf Coast pay zone is shown. In this case the tool never got very far from the boundary, so curves 14', 16', 18' and 20' are always widely separated and the predicted bed distance is always three feet or less. In this case, as in the previous log in FIGURES 1A-B, a large horn 28, 30 is seen on exiting the bed but not on entering even though the resistivity is almost the same in both cases. As this resistivity tool is symmetric, tool geometry can't explain the difference in horns at the boundaries. The most likely reason for the difference in horn formation is a difference in the geology, specifically the transition from one zone to another. Often, horns are not seen in field data when models predict that there should be horns, and when horns are seen they often don't resemble the horns in the model. These differences between the models and field data make quantitative interpretation of the horns very difficult.

CLAIMS

1. A method for drilling a wellbore in a selected formation at a desired distance from a boundary defining a change in resistivity with a drill string having a drill bit and a measurement-while-drilling resistivity device that propagates electromagnetic energy at one or more frequencies into the formation, receives electromagnetic energy that has propagated through the formation and produces a plurality of measurement signals from the received electromagnetic energy, characterized by:

(a) drilling the wellbore along a course in the selected formation by the drill string; and

(b) determining a distance between a point on the drill string and the boundary from the plurality of measurement signals.

2. The method according to claim 1 further comprising adjusting the drilling course in response to the determined distance from the boundary.

3. The method according to claim 1 or 2, wherein the plurality of measurement signals includes at least two measurement signals.

4. The method according to claim 1 or 2 or 3, wherein the electromagnetic energy is propagated into the formation at two frequencies.

5. The method according to claim 1 or 2, wherein the plurality of measurement signals include at least three measurement signals.

6. The method according to claim 4, wherein the two frequencies comprise a 400 KHz frequency and a 2 MHz frequency.

7. The method according to claim 1 or 4 or 5, wherein the plurality of measurement signals includes a signal that depends on the phase difference between the propagating electromagnetic energy and the received electromagnetic energy.

8. The method according to claim 1 or 5, wherein the plurality of measurement signals includes a signal that depends on the amplitude of the received electromagnetic energy.

9. The method according to claim 7 or, wherein the plurality of measurement signals includes a signal that depends on the amplitude of the received electromagnetic energy.

10. The method according to claim 1 or 2, wherein the electromagnetic energy is propagated into the selected formation at two frequencies, and wherein the plurality of measurement signals includes at least three measurement signals, wherein at least one such measurement signals depends on the phase difference between the

propagated electromagnetic energy and the received electromagnetic energy and at least one such measurement signal depends on the amplitude of the received electromagnetic energy.

11. The method according to claim 10, wherein the two frequencies are 400 KHz and 2 MHz.

12. The method according to claim 1 or 2, wherein the electromagnetic energy is propagated through a transmitter on the measurement-while-drilling device at a first frequency (f_1) and a second frequency (f_2) and the electromagnetic energy is received by two receivers on the measurement-while-drilling device longitudinally spaced from the transmitter.

13. The method according to claim 1 or 2 or 10, wherein the step of determining the distance comprises processing the plurality of measurement signals using a nonlinear regression scheme.

14. The method according to claim 12, wherein f_1 is 400 KHz and f_2 is 2 MHz.

15. The method according to claim 14, wherein the step of determining the distance comprises processing the measurement signals using a nonlinear regression scheme.

16. The method according to claim 1 or 2 or 15 further comprising:

(i) determining resistivity of the selected formation from the plurality of the measurement signals; and

(ii) determining resistivity of a formation adjacent a bed boundary of the selected formation.

17. The method according to any of the above claims further comprising transmitting the measured signals uphole using a telemetry.

18. The method according to any of the above claims, wherein the distance is determined by the measurement-while-drilling device during the drilling of the wellbore.

19. The method according to claim 12 or 15, wherein the nonlinear regression scheme comprises a high angle dipping model inversion.

20. The method according to any of the above claims 17, wherein the selected formation is a hydrocarbon producing formation.

21. The method of claim 18, wherein the propagating and receiving electromagnetic energy is done at three or more longitudinal spacings on the drill string.

22. The method of claim 21, wherein the measurement signals comprise signals that depend on attenuation of the propagating electromagnetic energy for each said spacings.

23. The method according to claim 1 or 2 or 16, wherein the measurement signals are indicative of at least three depths of investigation.

24. A wellbore drilling method substantially as herein described with reference to the accompanying drawings.

The Patent Office

Application No:	GB 9611667.8	**Examiner:**	Mr A Oldershaw
Claims searched:	1 to 24	**Date of search:**	3 September 1996

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.O): G1N NCLA, NCLC, NCLE, NCLF, NCLH

Int Cl (Ed.6): G01V

Other: Online: WPI

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
X,&	GB2256715A	(BAKER HUGHES)	1 at least
X	GB2194345A	(TELECO)	"
X	WO92/22833A1	(BAROID)	"
X	US5241273	(SCHLUMBERGER)	"
X,&	US5230386	(BAKER HUGHES)	"
X	US5045795	(HALLIBURTON) see col.1 ll.34-39; col.2 ll.25-35	"

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
		E	Patent document published on or after, but with priority date earlier than, the filing date of this application.
&	Member of the same patent family		